The Cooperative Engagement Capability (CEC)

Transforming Naval Anti-air Warfare

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Introduction

Cooperative Engagement Capability (CEC) is a system which promises to transform naval surface warfare to a major extent.

An official description of the system states:

> Cooperative Engagement Capability (CEC) enables battle group ships and aircraft to share sensor data at speeds never seen before providing the entire battle group with a single integrated air picture. This revolutionary capability doesn't require additional radars or weapons but instead shares information with existing systems. CEC brings significant improvements in several areas:
>
> - Air contact tracking accuracy.
> - Continuity of track.
> - Air contact identification consistency.
>
> These pieces of information, collected and shared by assets throughout the battle group, increase the size of battle space protection. They enable the battle group to more accurately identify air contacts before they can threaten the battle group. Once CEC is installed on all the battle groups, every ship and *Hawkeye 2000*[1] in the battle group will be capable of seeing the same target many miles away. This could not happen using only the ship's own organic sensors.
>
> CEC extracts data from sensors aboard surface ships and aircraft throughout the battle group operating region and displays fire control quality data, within microseconds, to every asset in the battle group. Having a fire control quality track on a target as it approaches the battle group enables all ships to engage at their maximum intercept range, taking into account the performance characteristics of each of the missiles. CEC gives the battle group commander an umbrella to protect all the ships and aircraft in the battle group and extends that umbrella of protection well beyond the outermost sensors of the battle group.[2]

The principal functions of the system are outlined in Figure 1.

While the virtues of such a capability are not difficult to understand we might wonder how transformative CEC truly is from a larger perspective. Will it make a major difference in overall fleet capabilities? Will naval forces be enabled to operate effectively in threat environments they could not otherwise penetrate? Will joint commanders be able to employ naval forces much more effectively and flexibly to meet higher level objectives as a result of CEC?

Another question is to what extent CEC represents *operational transformation* as contrasted to *technological evolution.* Was CEC simply an unbidden gift of general technological advance or a capability the Navy sought to meet operational needs? Does it

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[1] The *Hawkeye 2000* is the current version of the Navy's E-2C carrier-based airborne early warning and command and control aircraft.

[2] Surface Warfare Directorate (N76), Office of the Chief of Naval Operations, May 15, 2003. Available online at <http://www.navy.mil/navydata/cno/n76/n76cooperative.html>.

represent a truly new and different vision of needs and how to meet them? Finally, we might ask how CEC affects the ability of naval forces to operate and contribute in a joint warfighting environment.

These questions have no simple and unequivocal answers. To understand them clearly we need to look back to the dawn of air warfare.

Background

The Earliest Air Defense Networks

In 1914 aircraft were extremely primitive in technology and limited in performance. Nevertheless, when war broke out in Europe these crude machines quickly proved their value for reconnaissance. Aviators eager to seize the initiative armed their airplanes for counter-air operations and initiated attempts at air-to-ground operations. Ground forces mounted cannon and machine guns on improvised high-angle mountings to defend against air attack and observation.

The desperate nature of the conflict led to unprecedented measures. Fledgling British and French air forces dropped small bombs on targets in the rear of the advancing enemy. Germany built high-flying rigid airships to send over England in an effort to erode British will to fight through night bombing raids. In 1917 the dramatic but costly airship raids were succeeded by strikes with multi-engined biplane bombers. Although no more than pinpricks by later standards the raids brought demands for air defenses. From late 1917 London was protected by the London Air Defence Area (LADA). By war's end LADA had evolved into the world's first integrated air defense system.[3]

The technology available to LADA's developers was primitive but their concepts were sophisticated. Interceptions of German radio transmissions provided timely raid warning. Ground observers, often drawn from the police, used visual and aural cues to locate raids and telephoned their observations to the nearest of 25 local plotting centers. The local plot evaluated the data and transformed it to standard coordinates before relaying it to the master air defense center in London. On the basis of the developing raid plot air defense commanders deployed more than 200 fighter interceptors and 250 guns to meet the threat.

LADA was networked but did not represent network-centric operation in the modern sense due to the limitations of the technology. The network's telephone links could only reach ground nodes, of course, although by war's end LADA's interceptors were starting to equip with voice radio receivers. But even when they were in the net, tactical nodes received information which was extremely limited and often badly wrong. At best the net provided a heads-up, leaving them to engage on their own and offering no broader picture or means for self-synchronization. This stemmed from LADA's limits of sensor data and ability to process it. Position and altitude could rarely be determined with an accuracy

[3] John Ferris, "Fighter Defence Before Fighter Command: The Rise of Strategic Air Defence in Great Britain, 1917-1934," *Journal of Military History* 63, no. 4 (1999); David Zimmerman, "Information and the Air Defence Revolution, 1917–40," *Journal of Strategic Studies* 27, no. 2 (Jun 2004), 370-94; Raymond H. Fredette, *The Sky on Fire: The First Battle of Britain, 1917-1918* (Washington: Smithsonian Institution Press, 1966).

better than several kilometers and identification of targets even as friendly or hostile was often inaccurate.

In addition to misidentified tracks the system was bedeviled by twin problems that have persisted to this day, false tracks and missed tracks. This meant that even the tactical warning the net could provide was frequently misleading. Despite its limitations LADA did contribute significantly to defending London, but it was able to do so in large part because of the severely limited capabilities of the German bombers, which flew at less than 70 knots and relied on visual navigation.

The Beginnings of Air Defense at Sea

At sea in World War I, aircraft remained largely restricted to reconnaissance roles, and even in these their performance was limited. In the 1920s a series of widely-publicized weapons tests in the United States (and less publicized tests elsewhere) demonstrated that bombs could sink warships, but incidentally confirmed the challenges involved in finding targets in the vastness of the ocean.

The U.S. Army and U.S. Navy (USN) both were very short on funds for research and development (R&D) between the world wars, and the greatest portion of what R&D money they did have went to developing aviation.[4] The Navy did pursue several developments aimed at providing air defense for the fleet but progress was slowed not only by money but also by threat perceptions. While it is obvious in retrospect that air defense should have been near the very forefront of naval concerns the Navy was in effect sandbagged by technological developments which to large extent it had helped foster. In the five years between 1933 and 1938, the range, payload, and speed of bombers more than doubled. When this technological advance was coupled with the technique of anti-ship dive bombing—pioneered by the Navy—a threat which not long before had seemed sharply limited suddenly loomed frighteningly large.

Considerations of safety as well as funds limited air defense testing but there were increasingly disturbing signs in the tests which the Navy was able to run. Any remaining doubts were dissipated in 1940 as Britain's Royal Navy (RN) sustained severe losses to attacks by the German and Italian air forces.

The Navy response to the air threat was channeled by both technological and bureaucratic factors. Aircraft were the responsibility of the Bureau of Aeronautics, weapons and their control systems of the Bureau of Ordnance (BuOrd), and search radar of the Bureau of Engineering (BuEng).[5] The responsibility of BuEng for radar had come about more or

[4] William D. O'Neil, "Military Transformation as a Competitive Systemic Process: The Case of Japan and the United States Between the World Wars," CRM D0008616.A1 (Alexandria, Virginia: Center for Naval Analyses, June 2003). Available online at <http://www.cna.org/documents/D0008616.A1.pdf>. The Air Force did not emerge as a formally independent service until 1947 and the Marine Corps was largely subordinated to the Navy up to World War II.

[5] In 1940 the Bureau of Engineering was merged with the Bureau of Construction and Repair to form the Bureau of Ships. The merger was prompted by problems stemming from inadequate integration of advanced steam propulsion plants with new-design ships, as described in Historical Section, "An Administrative History of the Bureau of Ships During World War II" (Washington: Bureau of Ships, 8 Aug 1952), I:17-76.

less by accident, as an outgrowth its communications work. The new technology lay partly beyond the bureau's normal domain, which contributed to radar's somewhat halting development within the Navy.[6]

By the time of Pearl Harbor, the Navy had modern streamlined monoplane carrier-based fighter aircraft capable of serving as interceptors as well as a fast-firing five-inch dual-purpose (anti-air and anti-surface) gun controlled by a complex analog-computer fire control system with telescopic optical sighting and rangefinding instruments.[7] Efforts at development of a heavy machine gun for close-in defense had met with limited success but BuOrd had very quickly adapted European 20 mm and 40 mm guns of sound design to American production and was supplying them to the fleet.[8] Radar installation had begun in 1940 and by 10 days after Pearl Harbor 79 radars had been installed in Navy ships, including 46 sets with air search capabilities, with more being fitted at a rate of 14 per week.[9] Anti-air fire control radars, providing accurate range information and moderately good elevation and azimuth for five-inch gunfire, were starting to come off production lines.[10] Voice radio sets operating in the HF and lower VHF bands were widely fitted in aircraft and ships.[11]

While not ahead in every class of equipment, overall the U.S. Navy was superior to every other navy in the world in air defense potential at that point. Yet there were very serious gaps in its capabilities, reflecting not only technological limits and the residue of earlier funding shortages but failure to come to grips with essential information problems.

World War II [R]evolution in Air Defense in Britain

The advent of radar created the potential for a revolution in air defense both ashore and at sea, but much further operational and technical development was needed to realize the potential fully.

While Britain had been a relatively late starter in the radar race, a focused and well supported effort brought it first to the finish line. A quite primitive but effective "Chain Home" (CH) radar network was put into service on the very eve of war in 1939. By mid-1940 Germany's conquest of France had set the stage for an epic aerial confrontation as Hitler tried to set the stage for an invasion across the English Channel.

Operating at wavelengths of 7.3 to 16.7 meters (22 to 50 MHz, in the HF and low VHF radio bands), a CH station was a massive affair with multiple sets of tall transmitting and

[6] David Kite Allison, *New Eye for the Navy: The Origin of Radar at the Naval Research Laboratory* (Washington: Naval Research Laboratory, 1981); Louis Brown, *A Radar History of World War II: Technical and Military Imperatives* (Bristol: Institute of Physics Publishing, 1999), 64-7.
[7] David A. Mindell, "Anti-Aircraft Fire Control and the Development of Integrated Systems at Sperry, 1925-1940," *IEEE Control Systems* 15, no. 2 (April 1995), 108-13; *Idem*, *Between Human and Machine: Feedback, Control, and Computing Before Cybernetics* (Baltimore: Johns Hopkins University Press, 2002).
[8] Buford Rowland and William B. Boyd, *The U.S. Navy Bureau of Ordnance in World War II* (Washington: Bureau of Ordnance, U.S. Navy, 1953), Chapter 11.
[9] Allison, 181.
[10] Rowland and Boyd, 426-7.
[11] Louis A. Gebhard, *Evolution of Naval Radio-Electronics and Contributions of the Naval Research Laboratory* (Washington: Naval Research Laboratory, 1979): 96-8.

receiving towers.[12] Accuracy was very limited—12° azimuth errors and two-mile range errors being not uncommon, while height indications could be out by thousands of feet. Raid size estimates often were significantly in error.[13] Extensive multipath reflections from terrain caused many blind spots in the coverage of all but the most favorably sited stations. Operation was complex and even the best operator teams could generate no more than six target reports per minute.

The British radar air-defense pioneers, drawing on World War I experience as well as interwar experiments and analyses by early operations research scientists, recognized the need to translate the spotty and error-ridden radar (and observer and pilot) *reports* into action *information*.[14] It was their solution of this problem that transformed Chain Home from a collection of crude *radar sets* into an effective air defense *network*. Radar operator readings were transformed and rectified with electro-mechanical computers before being reported by telephone to a "Filter Room" at Bentley Priory, north of London.[15] Filter operators placed time-coded counters representing the reports on a large map, very much as reports had been plotted in LADA's center more than two decades before. For the new war, however, a vital new step was added as "filterers" (originally non-commissioned officers but later replaced with officers having technical qualifications) deconflicted and smoothed reports to produce a best-estimate track. Ideally, plots were formed from range cuts from two or more radar stations, since range accuracy was much better than azimuth accuracy, but this involved complications and opportunities for confusion. In particular it was up to the filterer to determine whether two nearby reports represented one track, two close tracks, or a track that had split into two.

Under the direction of the Filter Room watch officer the filtered tracks were reported or "told" to the Operations Room where they were plotted together with their own-force position data. (A direction-finding system linked to the fighters' VHF radios provided fairly accurate tracks.)[16] The air defense commander made threat assessments and tracks were told to group and then sector operations rooms for action.

Anyone familiar with modern air defense operations will recognize how little the fundamental process has changed, even though the mechanization has been entirely transformed.

In present-day terms we can recognize the Filter Room as a fusion center. In principle, routing all radar reports to a single center for fusion ensured maximum use of all data. In practice the high workload involved in filtering meant that the system was vulnerable to

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[12] S[ean] S. Swords, *Technical History of the Beginnings of RADAR*, ed. Brian Bowers, vol. 6, IEE History of Technology Series (London: Peter Peregrinus, 1986), 188-236; Louis N. Ridenour, *Radar System Engineering*, ed. Louis N. Ridenour, Radiation Laboratory Series (New York: McGraw-Hill Book Co., 1947), 175-80; B. T. Neale, "CH—The First Operational Radar," in Russell W. Burns, ed., *Radar Development to 1945* (London: Peter Peregrinus & Institution of Electrical Engineers, 1988).
[13] Air Ministry, *The Origins and Development of Operational Research in the Royal Air Force*, Air Publication 3368 (London: Her Majesty's Stationery Office, 1963), 14-15; Louis Brown, 111.
[14] Zimmerman, Op. cit.
[15] Ridenour, 226-8; Swords, 253.
[16] Louis Brown, 110.

saturation in periods of high raid density. After intense debates the primary burden of filtering was moved to individual group centers.[17] This alleviated the risks of saturation but presented the problem of coordination and handoff across the seams between adjacent groups.

The Battle of Britain focused attention on the fighter-interceptor as the main instrument of air defense. Britain's army had paid even less attention to anti-aircraft artillery (AAA) than most between the wars.[18] AAA accomplished relatively little in the campaign and received credit for less still. The outputs of the CH radars as passed through the filter centers were adequate to permit vectoring interceptors but were of much more limited help to AAA. A "gun-laying radar" had been devised but it was too primitive to be of significant value, especially given the other limitations of British AAA at this point. AAA remained only loosely tied to the air defense network until later in the war.

The RN was slower than the Royal Air Force (RAF) to develop radar. But it was installing basic yet useful Type 79 air warning sets at war's outbreak in 1939—at a time when the USN had just put its first experimental sets to sea for test.[19] The vulnerability of RN surface ships to German and Italian dive- and torpedo-bombers was soon revealed as a grave threat to Britain's maritime supremacy. As a result both of bad judgement and misfortunes of timing the RN's air defense posture was quite poor. Its carrier aviation was little developed and its shipboard AAA systems were inadequate both in quantity and quality.[20] (This was of course more than two years before Pearl Harbor and the USN was in little if any better shape for overall air defense at that point.)

Influenced by the RAF example and spurred by the severe German and Italian air threat, RN officers at sea began improvising very crude radar-based systems for directing fighters early in 1940.[21] By the middle of 1941 the basic procedures had been developed and were being taught at a school for new fighter direction officers (FDOs). Fighter direction evolved in parallel with improvements in surface situation plotting and means for designating targets to shipboard AAA systems.[22]

World War II [R]evolution in USN Air Defense: CIC

While relations had sometimes been strained between the two world wars, Britain and the United States developed very close ties under the mutual threat of Nazi aggression, and

[17] Zimmerman, 387-92; Air Ministry, 16-8.
[18] Stuart Bennett, *A History of Control Engineering, 1930-1955* (Stevenage, U.K.: Institution of Electrical Engineers, 1993), 115; Louis Brown, 118-9.
[19] J. S. Shayler, "Royal Navy Metric Warning Radar, 1935-45," Monograph 4, in F[rederick] A. Kingsley, ed., *The Development of Radar Equipments for the Royal Navy, 1935-45* (Basingstoke: Macmillan Press, 1995).
[20] David K. Brown, *Nelson to Vanguard: Warship Design and Development, 1923-1945* (Annapolis: Naval Institute Press, 2000), 207-9; Thomas C. Hone, Norman Friedman, and Mark D. Mandeles, *American & British Aircraft Carrier Development, 1919-1941* (Annapolis: Naval Institute Press, 1999).
[21] R. S. Woolrych, "Fighter-Direction Matériel and Technique, 1939-45," in *Applications of Radar and Other Electronic Systems in the Royal Navy in World War 2*, ed. F[rederick] A. Kingsley (Basingstoke: Macmillan Press, 1995).
[22] A. E. Fanning, "The Action Information Organisation," in *Ibid.*; H. W. Pout, "Weapon Direction in the Royal Navy," in *Ibid.*

particularly after the Fall of France in mid 1940. The American people and their political leaders hoped that they could bring about the defeat of Hitler by serving as democracy's arsenal rather than its manpower pool, but relatively few doubted that Hitler had to be defeated for America's safety. In the eyes of Britain's leadership the west was the one sector of brightness on a very dark horizon.

In this environment a remarkably intimate and intense sharing of military technological and operational resources developed in the 15 months preceding Pearl Harbor. The famous Tizard Mission of September 1940 gave American radar developers a head start of at least a year toward development of microwave radar. More immediately, close liaison between the USN and RN (as well as RAF) greatly accelerated American progress in air defense for the fleet. By mid 1942 the U.S. Navy would need all the aid it could get in this area. By 1944, building first on British experience and then its own, the USN had developed a formidable capability.

USN fleet air defense in 1944–45 included very important elements of net-centric warfare. Task fleets and forces operated in extended formations and dispositions calculated to maximize air defense and strike capabilities. Aboard the ships of the force, combat information centers (CICs) plotted all available information about position and identity of aircraft and other targets.[23] After evaluation and filtering by CIC officers these tracks provided the basis for vectoring aircraft to intercept as well as indicating targets for AAA engagement. Figure 2, reproduced from a contemporary manual, outlines the functions of the CIC. While radar is shown as only one among many sources of information, it was by far the predominant one in air defense. In fact, the CIC had originally been titled "Radar Plot."

As Figure 2 suggests, CIC's main focus was on its own ship's data and operations. (Figure 3 traces the main information flows between the CIC and the remainder of the ship.) The need for force-wide coordinated defense was clearly recognized. In the words of the wartime doctrine, "Maximum combat efficiency of individual ships and task organizations can best be attained through full utilization of all available sources of combat intelligence."[24] Technological limitations forced compromises, however. At best, communications with the CICs of other ships in the force were restricted to a few voice channels, usually only four. (See Figure 4 for a schematic diagram of inter-unit information flows.) Tracks held by radars on other ships were reported (told) only once a minute—even at World War II speeds this meant that they were plotted only at intervals of four miles or more. Tracks reported by other ships might sometimes be out by miles owing to uncertainties about the relative positions of reporting and own ships.

[23] For the development of CIC and fighter direction in the USN during World War II see David L. Boslaugh, *When Computers Went to Sea: The Digitization of the United States Navy* (Los Alamitos, Calif.: IEEE Computer Society, 1999), 5-52; Norman Friedman, *U.S. Naval Weapons: Every Gun, Missile, Mine and Torpedo Used by the U.S. Navy from 1883 to the Present Day* (Annapolis: Naval Institute Press, 1982), 91-4; and Henry E. Guerlac, *RADAR in World War II* (Los Angeles/New York: Tomash Publishers/American Institute of Physics, 1987), 927-39.

[24] "Current Tactical Orders and Doctrine, U.S. Fleet," Change 4, USF 10A (Washington: Headquarters of the Commander in Chief, U.S. Fleet, 14 Jun 1945), § 6120.

Because of these limitations, fighters could be directed only from the CIC of a ship which held radar contact on the fighters and the target. If radar contact were lost, control had to be transferred to another ship or the interception missed.[25]

Despite these problems USN fighter direction functioned reasonably effectively, aided by the slow speeds of threat aircraft and application of massive resources of high-quality manpower. There were, however, significant numbers of instances in which threats were not reported by any ship prior to coming in range of short-range weapons. In several cases ships were damaged or even sunk by attackers which were not detected at all.

Even when threats were detected normally the process of engaging them with shipboard AAA was cumbersome and error-ridden. To destroy an attacker—particularly a kamikaze human-guided missile—an AAA shell had to be placed with an accuracy of a few feet at least. But even own-ship air search radars rarely reported targets with an accuracy better than 1,000 yards.[26] Thus there was an accuracy gap of roughly 1000:1 which had to be closed in order to deliver effective AAA fire.

Targets were assigned to AAA directors and gunners on the basis of CIC tracks. The first problem was for the shooter to acquire the target with its own radar and/or visual sensors. Only the directors for the largest AAA weapons had radars in World War II, although by war's end radar directors for lighter weapons were nearly ready. Whether directors were visual or radar (or mixed) the process of transferring the target information, acquiring it, establishing track, and getting a firing solution was an elaborate one, involving multiple stages. One early post-war document (referring to a particular set of systems then in wide use) describes 18 steps, each involving human action.[27]

Once targets were taken under fire, the effectiveness of AAA was severely limited by lack of precise data. By war's end it took several thousand rounds of 40 mm heavy machine gun fire to kill a single aircraft—even though a single hit by one of the two-pound shells was usually all that was required to splash a lightly-built Japanese aircraft. The burst of a 55-pound five-inch shell within a dozen feet or more would usually destroy an attacker but about 300 proximity-fuzed five-inch rounds were needed on average to achieve a kill against a "kamikaze" human-guided missile.[28] This was not primarily a matter of target maneuvers: 285 proximity-fuzed 90 mm rounds were required, on average, to bring down a non-maneuvering German V-1 "buzz bomb" cruise missile.[29]

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[25] For some of the vicissitudes of fighter direction see John Monsarrat, *Angel on the Yardarm: The Beginnings of Fleet Radar Defense and the Kamikaze Threat* (Newport, Rhode Island: Naval War College Press, 1985), especially 147, 165, 172, and 173. The book is a memoir of the World War II service of a fighter direction officer aboard a USN carrier.

[26] World War II USN air search sets had intrinsic errors of the order of 100 yards in range and a few degrees in azimuth. Operational accuracy was ordinarily not this good, even in range, due to errors in alignment, calibration, and operator reading.

[27] Bureau of Personnel, *Principles of Naval Ordnance and Gunnery*, NavPers 10783 (Washington: Government Printing Office, 1959), 211-9.

[28] Commander in Chief, U. S. Fleet, "Antiaircraft Action Summary, Suicide Attacks," COMINCH P-009 (Washington: Headquarters of the Commander in Chief, Apr 1945), 210.

[29] Mindell, *Between Human and Machine*, 257.

Radar (and the radar proximity fuze) made it possible to defend the fleet against air attack in World War II, but only just. The information that early radar could provide was critical but crude and limited. As U.S. Navy leaders looked toward an onrushing age of much higher performance threats they felt deep concern.

Post-War [R]evolution in USN Air Defense: NTDS

The decade following the close of World War II brought dizzying change in air threats. Speeds leapt from 300 to more than 600 knots and altitudes soared from 25,000 to 40,000 feet—with even higher performance clearly in sight. For the first time it appeared that the Continental United States might be within reach of air attack. Most ominous of all, nuclear threats emerged.

Manual air defense plots clearly were inadequate in the new age. A single plotting team could handle no more than 12 tracks effectively at any one time, and even at best was prone to errors. Fleet exercises showed that up to 30 percent of threats never were detected at all. The U.S. Air Force (USAF), USN, and British and Canadian Navies all attempted to develop automated electronic systems to perform the data-handling functions of filter centers and CICs. First to see service was the USAF Semi-Automatic Ground Environment (SAGE), a massive system built around vacuum-tube computers.

The Navy spurned a proposal to build a large ship dedicated to taking SAGE to sea and instead pushed the digital computing state of the art to develop its own much more compact (but comparably capable) Naval Tactical Data System (NTDS), a semi-automated CIC.[30] The original concept was that NTDS detection and tracking would be highly automated and integrated, but the digital computers of the late 1950s were far less powerful than those used to play video games today, and technological limitations forced compromises. As a result considerable manual supervision and intervention was necessary.

Despite the limitations of its technology and its hasty, five-year development, NTDS was highly successful. The Fleet's ability to handle large numbers of fast-moving tracks rose dramatically. Real-world proof of the power of NTDS came in less than a decade. The Vietnam War saw only limited air threats to naval forces but brought demands for high-quality surveillance of large numbers of friendly (and some neutral) tracks over the Gulf of Tonkin and North Vietnam. Manual CICs proved unable to handle this load but NTDS did so with an accuracy and timeliness that made it possible to distinguish and engage the few hostile tracks that did appear. The Vietnam War also brought the first major steps toward automation of detection and tracking in NTDS.

One of NTDS' major innovations was an automatic computer-to-computer data link, called Link A (in NTDS terminology) or NATO Link 11, which gave all ships direct access to all track-store data in the force.[31] (Later the Joint Staff established a set of approved "tactical digital information link" (TADIL) standards, with Link A becoming

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[30] The story of NTDS is told very well by Boslaugh, *Op. Cit.*, from which most of the material here is drawn.

[31] A *data link* is defined by its set of standardized message formats and transmission rules, usually implemented in software in a controlling computer. Link information is transmitted via one or more kinds of communications channels, usually radio. When only one communication channel is associated with a given link the two often become merged in common usage.

TADIL A.) When several ships held track on the same target only the highest quality track was displayed.

NTDS was too massive for aircraft to carry, but the E-2 carrier-based airborne early warning (AEW) aircraft did carry a system which permitted it to link to NTDS, aiding early warning and raid identification.

NTDS was accompanied by the introduction of new radar systems. The SPS-49 provided long-range two-dimensional air search and supported control of fighters and other aircraft. It went aboard most ships of destroyer size and above. In addition, aircraft carriers and missile ships got the SPS-48, which scanned in elevation as well as bearing to provide a three-dimensional air picture. Advances in electronics and digital technology brought improvements in these radars as well as NTDS through the 1960s and early 1970s.

But for all the successes of NTDS and the new radars serious holes remained in Fleet anti-air warfare (AAW) capabilities. The accuracy with which NTDS could track targets depended critically on the accuracy with which the relative positions of reporting ships could be determined as well as the accuracy with which their radars were aligned and calibrated. Accuracy problems often resulted in dual tracks—two or more reports of the same target could easily be mistaken for different tracks because they appeared in what seemed to be different positions. In addition, a disturbing number of targets still failed to be detected at all.

NTDS provided a rapid assessment of the threat potential of each track and flagged those of greatest concern to enable rapid assignment of weapons in accordance with an established doctrine. But accuracy problems also slowed the handover to the pencil-beam radars of ship and aircraft fire control systems, which might have to search for crucial seconds before finding the target which had been passed.

New Threats and New Technology: Aegis

The combination of NTDS, the new generation of shipboard radars, the E-2 AEW aircraft, the F-4 interceptor, and anti-air guided missile systems transformed Fleet AAW. Wielding these systems an aircraft carrier battle group could establish effective control over a volume of airspace extending more than 100 miles in every direction, enabling it to conduct strike operations in the face of jet-speed air threats.

This capability, however, naturally provoked the Soviet Union and other hostile nations to redouble their efforts. Direct weapons delivery by manned aircraft appeared to be out of the question, but attacks with missiles or high-performance “robot kamikazes” offered greater potential. The Soviets sought to saturate Fleet AAW with masses of Mach 3+ anti-ship cruise missiles (ASCMs), and with very low-altitude ASCMs that could “hide” in the radar clutter near the sea surface.

Thus, in the 1960s the USN began to seek new systems based on new technology. The F-14 interceptor and the E-2C, an E-2 airframe with an advanced radar better able to pick targets out of sea clutter, were important aspects of this.[32] But a fundamentally better

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[32] For a brief technical description of the APS-125, the original E-2C radar, see John Clarke, “Airborne Early Warning Radar,” *Proceedings of the IEEE* 73, No. 2 (Feb 1985), 312-24. Evolution of the E-2C is

shipboard AAW system also was needed. After some initial disappointments the Navy embarked on the development of what was to become the Aegis Weapon System.[33, 34]

The Aegis system is built around a very powerful S-band phased-array radar, designated the SPY-1, which can redirect its beam to any elevation and bearing instantaneously.[35] With no need to rotate for scanning the arrays could be large enough to give high gain and narrow beamwidth. Together with high power and sophisticated computer signal processing this endows the Aegis SPY-1 radar with high performance both as a search and fire control radar, nearly a unique combination. And with one radar performing both functions the handoff from search to fire-control tracking is far surer and swifter.

The Aegis Weapon System is a totally integrated shipboard combat suite which, among other things, performs all of the functions of an advanced NTDS. In addition to the SPY-1 radar, Aegis diversifies its capabilities with an advanced version of the SPS-49 two-dimensional rotating air search radar, operating in a different frequency band. The Aegis Command and Decision System (which performs the NTDS-like functions) integrates the data streams from the SPS-49, electronic warfare, antisubmarine, and other sensors with those of the SPY-1 and shares resulting track information with other ships in the force via Link 11 as well as the newer NATO Link 16.[36] Link 16, known as TADIL J in U.S. terminology, is transmitted over JTIDS or MIDS UHF radio systems. It offers wider bandwidth, much greater jamming resistance, and a variety of other technical improvements, but remains largely track oriented.

CEC

Aegis brought a sweeping improvement in the AAW capabilities of individual ships and helped greatly to tilt the AAW balance strongly in the Fleet's favor. But new technological opportunities offered the possibility of extending capabilities still further.

The key to CEC is the ability to move from track telling to transmitting complete radar data, dwell by dwell.[37] (Broadly, a *dwell* is a single radar "look" at a target, which may

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conveniently summarized in Obaid Younossi, et al, "The Eyes of the Fleet: An Analysis of the E-2C Aircraft Acquisition Options," MR-1517-NAVY (Santa Monica: RAND, 2002), 10.

[33] *Aegis* is not an acronym. The *αἰγίς* (Greek) or *ægis* (Latin) was the shield of the mythological god Zeus (Jupiter) and thus represents a sure defense.

[34] For an overview of USN surface (not air) AAW technological development up through the 1980s see George F. Emch, "Air Defense for the Fleet," *Johns Hopkins APL Technical Digest* 13, No. 1 (1992), 39-66. It is written from the perspective of involvement by Johns Hopkins Applied Physics Laboratory, but APL was involved in most of the major developments. Also see Norman Friedman, Op. Cit., 142-83.

[35] For overviews of the SPY-1 radar see John A. Adam, "Pinning Defense Hopes on Aegis," *IEEE Spectrum* 25, no. 6 (Jun 1988), 24-7, as well as Richard L. Britton, et al, "AN/SPY-1 Planned Improvements," *IEEE EASCON 1982*, 379-86. The functions and structure of the Aegis Combat System are outlined in James D. Flanagan and George W. Luke, "Aegis: Newest Line of Defense," *Johns Hopkins APL Technical Digest* 2, no. 4 (1981), 237-42. These articles refer to the original versions; more than 100 Aegis systems have now been delivered over more than two decades and the latest versions are considerably advanced over early models. The earlier versions remaining in the Fleet have also been substantially upgraded.

[36] "Introduction To Tactical Digital Information Link J and Quick Reference Guide (TADIL J)," FM 6-24.8, MCWP 3-25C, NWP 6-02.5, AFTTP(I) 3-2.27 (Fort Monroe: Training and Doctrine Command, Jun 2000).

[37] For overviews of CEC see "The Cooperative Engagement Capability," *Johns Hopkins APL Technical*

involve multiple pulses in rapid succession but at the same beam position.) There were three major factors in this, all stemming from advances in computer speed:

- Faster digital components have made it possible for radar receivers to become increasingly digitized, so that the radar data were actually measured and processed in digital form. Thus, it was easy to extract data for transmission via digital data link.
- Computerized digital communications systems permit far faster transmission speeds without great increases in physical bandwidth or transmitter power.
- With fast computing widely available each unit can process all of the radar dwell data individually. By using the same algorithms each unit gets the same result and is assured of seeing the same picture as all others.

By combining the radar data from a number of units many important gains could be made, including:

- By dynamic "intelligent averaging" of radar data—weighting each data point according to the accuracy of the radar—it is possible to get a more accurate and complete track than any individual radar could provide.
- With accurate data from others a unit whose radar does not yet hold a target can point its radar precisely so as to pick it up even at the very limits of radar visibility.
- With highly accurate data a unit may be able to engage a target it does not hold track on with its own radar.

These three core CEC capabilities are illustrated by Figure 1. Figure 5 shows an actual example of how CEC combines radar dwell data to produce a composite track.

One interesting CEC potential was that of improving tracking of stealthy targets. Often stealthy aircraft or missiles are much more visible from some angles than others. No one radar is likely to see a stealthy target from a favorable angle for more than a few dwells in succession, but by adding up the contributions of many radars it may be possible to get a solid track.

CEC was conceived before net-centric warfare (NCW) but it fit very closely into the NCW framework. In fact, CEC was on the mind of Vice Admiral Arthur K. Cebrowski, USN, at the time he formulated the NCW concept.[38] As he emphasized, with CEC those units that do not have the SPY-1 or the E-2C's airborne radar could nevertheless have a complete and highly accurate tactical picture as well as the information necessary for effective weapon engagements. Thus, units can effectively coordinate and synchronize their tactical action without need for central direction. The only limitation is that the common tactical picture extends only as far as the sensor reach of the units participating in the CEC network. Thus, the power of CEC increases with density of coverage.

Digest 14, no. 4 (1995), 377-96; M.J. O'Driscoll and J.A. Krill, "Cooperative Engagement Capability," *Naval Engineers Journal* 109, no. 2 (Mar 1997), 43-57; and Phil Balisle and Tom Bush, "CEC Provides Theater Air Dominance," *Proceedings*, U.S. Naval Institute (May 2002).

[38] The author of this case study had frequent conversations with VADM Cebrowski at that time and the subject of CEC as an important enabler of NCW came up repeatedly.

Like many systems involving very advanced technology, CEC encountered difficulties in development. These resulted in some delays in full deployment and a modest rise in cost, but the total cost per unit, at less than $17 million, remains affordable.[39]

CEC and the Single Integrated Air Picture

Stories of transformation rarely have any definite stopping place, for transformation is a process rather than an event. The AAW problems that the USN has wrestled with since the late 1930s have their counterparts ashore as well. And as the naval and land battlespaces have increasingly merged into a single joint battlespace it has become increasingly important for all units, in whatever environment, to have a common air picture.

One approach might be to extend CEC to all units, but this is neither technically feasible nor affordable at present. Instead the Department of Defense (DOD) has fostered development of a joint system known, descriptively, as Single Integrated Air Picture (SIAP).[40] SIAP and CEC are closely tied together and CEC has strongly influenced the SIAP approach. At this time much of SIAP's emphasis is on establishing an operational framework for common track telling, something on the order of a super NTDS, but in the longer run it seems likely that SIAP and CEC will merge into a common all-service joint system operating at the sensor data level.

CEC in Perspective

From its origins in World War I, air defense has hinged on four major information functions:

- *Sensing.* Gather all possible relevant data on the position, movements, and identity of all the objects in the air space.
- *Filtering and tracking.* From the sensor data assemble as comprehensive, complete, coherent, and accurate an air picture as possible, compensating for all the defects in the data.
- *Assessment and decision.* On the basis of the air picture assess the situation and decide on the proper course of action in accordance with doctrine and command instructions.
- *Assignment and handoff.* Transmit assignments of targets to weapons systems as decided and handoff data as necessary to permit prompt, accurate, and effective engagement.

These needs were understood, at least dimly, from the very beginning, and all of these functions were performed, as well as existing technology allowed, as early as 1917 in Britain. The development of primitive radars in the late 1930s and early 1940s completely revolutionized the sensing function and laid the basis for transformation of the other, downstream functions. Their transformation was carried through, among other

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[39] Government Accountability Office, "Assessments of Selected Major Weapon Programs," GAO-05-301 (Washington: Mar 2005), 39.
[40] SIAP System Engineering Task Force, "SIAP Plans, Progress, and Recommendations," Technical Report 2002-004, April 2002.

places, in the USN World War II CICs. A major complicating factor was the inherently distributed nature of the problem, with no one unit having all the sensor data or all the weapons needed. This was resolved by an early, partial network-centric approach in which all radar-equipped units participated with a large degree of self-synchronization.

Although the World War II system worked well within its limits, sensing as well as filtering and tracking capacities were inadequate even for late-war threats. Improved radars helped sensing in the post-war period but threw even more load on filtering and tracking. NTDS represented a major step in filtering and tracking, as well as improving the remaining functions and network operations.

The period of the 1970s and 1980s brought major advances in sensors, much of it due to advances in digital technology. Technology for networked filtering and tracking among units in a force also advanced but not in pace with sensor developments, and thus the force could not make full use of the increased flow of sensor data. CEC has swept away this limitation almost entirely and in the process has enabled optimum force-wide assignment and handoff.

CEC and Transformation

Most cases of notably transformative technologies are associated with vehicles, weapons, and/or sensors. CEC is none of these things and yet figures on every list of major transformative innovations by virtue of its ability to increase the utilization and effectiveness of existing and future sensors and weapons.

CEC has not undergone a major test in combat and it is possible that it never will. But we have seen how it is a descendent of the World War II innovation of CIC and the 1950s innovation of NTDS, both of which proved their transformative capacity dramatically in combat environments. These close historical precedents can help cast some light on questions frequently asked about transformative innovations such as CEC.

Appendix: The Track Movie

In order to clarify the fundamental processes involved in tracking it is helpful to think in terms of a familiar analogy, the motion picture.

In essence, the air defense system gets a series of snapshots of the air action. If snapshots come from one good camera at a rapid, constant rate it is relatively straightforward to merge them into a movie accurately showing the action. But in air defense we usually have only an irregular series of snapshots from various “cameras” that may introduce serious distortions. The problem is to make a “track movie” out of these and do so in real time, without significant delay.

In World War II CICs, radar operators, plotters, CIC evaluators, and FDOs acted as “animation artists,” sifting through the snapshots and drawing an animated film of the track. Starting in the 1950s computers have taken over more and more of the animation process. At the same time the radar “cameras” have grown better and more precise, and better navigation has helped as well. So the digital track movies of today are better than their grainy, human-drawn World War II antecedents.

Nevertheless, they remain “animations” that cannot always accurately represent the actual tracks in every detail. And there is always more than one possible track animation that could be drawn on the basis of the same snapshots.

Abbreviations and Acronyms

AAA	Antiaircraft artillery
AAW	Anti-air warfare
AEW	Airborne early warning
ASCM	Antiship cruise missile
BuEng	Bureau of Engineering
BuOrd	Bureau of Ordnance
CEC	Cooperative Engagement Capability
CH	Chain Home [radar]
CIC	Combat information center
FDO	Fighter direction officer
HF	High frequency (radio band)
JTIDS	Joint Tactical Information Distribution System
LADA	London Air Defence Area
MHz	Megaherz
MIDS	Multifunctional Information Distribution System
NCW	Network-centric warfare
NTDS	Naval Tactical Data System
RAF	[British] Royal Air Force
RN	[British] Royal Navy
SAGE	Semi-automatic Ground Environment
SIAP	Single Integrated Air Picture
TADIL	Tactical digital information link
UHF	Ultra high frequency (radio band)
USAF	United States Air Force
USN	United States Navy
VHF	Very high frequency (radio band)

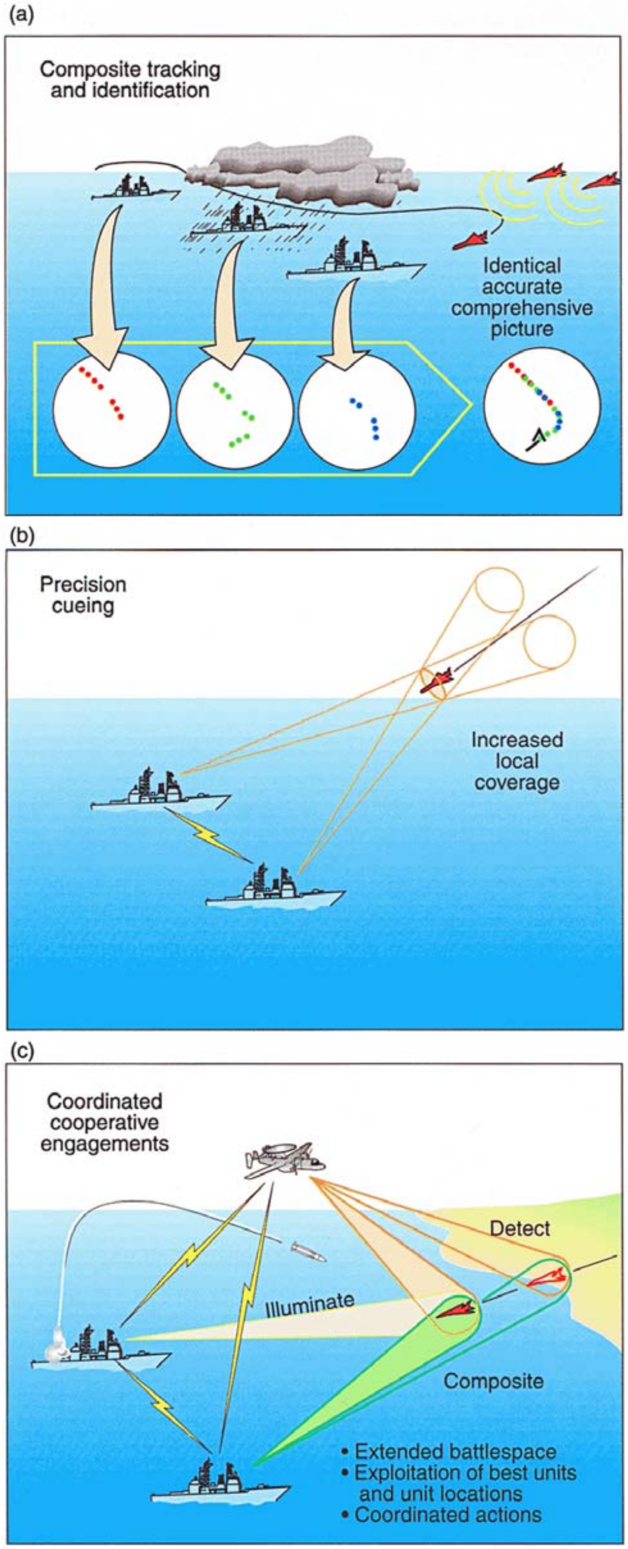

Figure 1. CEC's Principal Functions

Source: "The Cooperative Engagement Capability," *Johns Hopkins APL Technical Digest* 16, No. 4 (1995): 377-96.

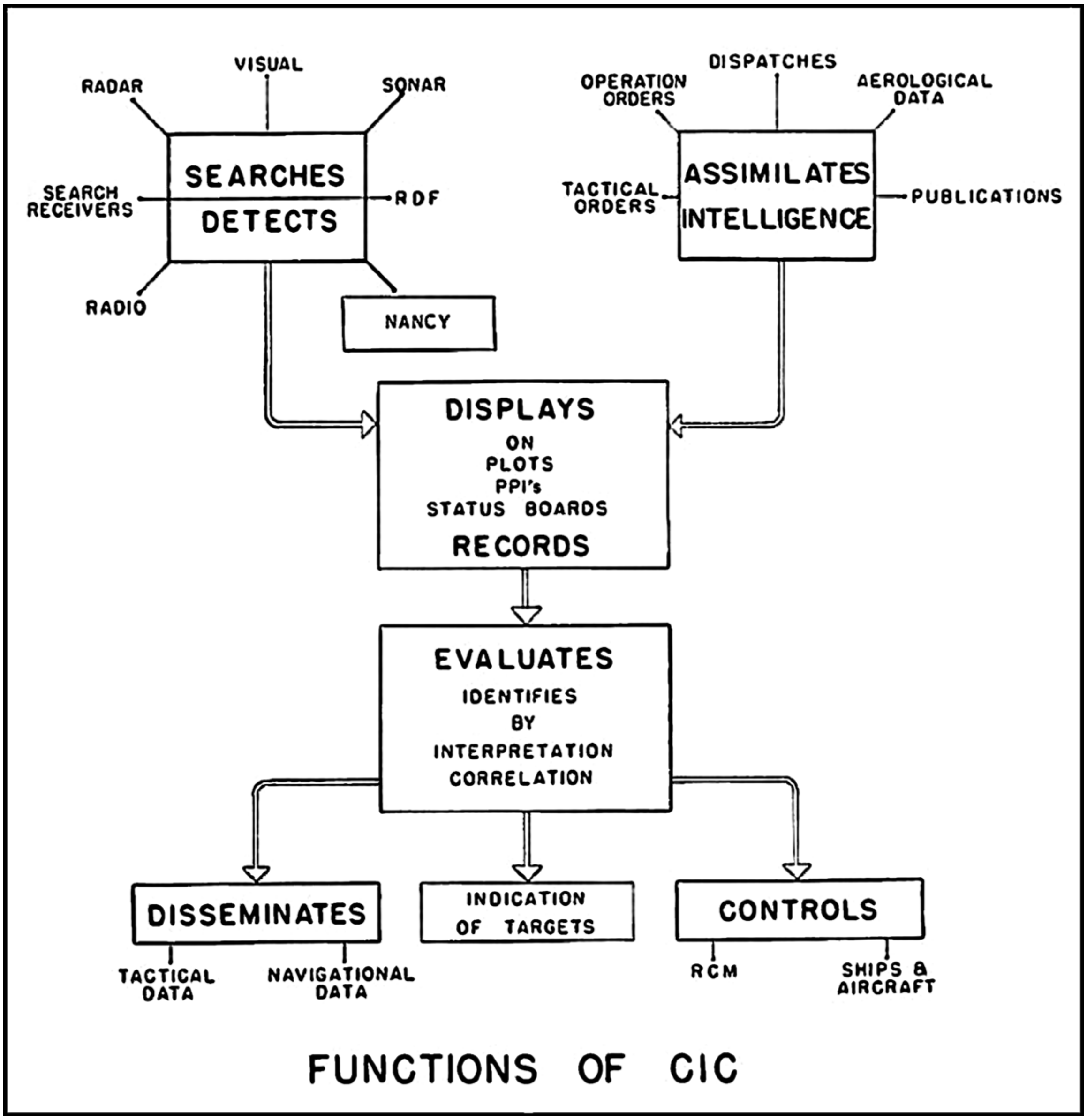

Figure 2. CIC Functions

Source: "CIC Manual (RADSIX)," Radar Bulletin No. 6, COMINCH P-013 (Washington: Headquarters of Commander in Chief, U.S. Fleet, 7 Jul 1945), http://www.history.navy.mil/library/online/cicmanual.htm.

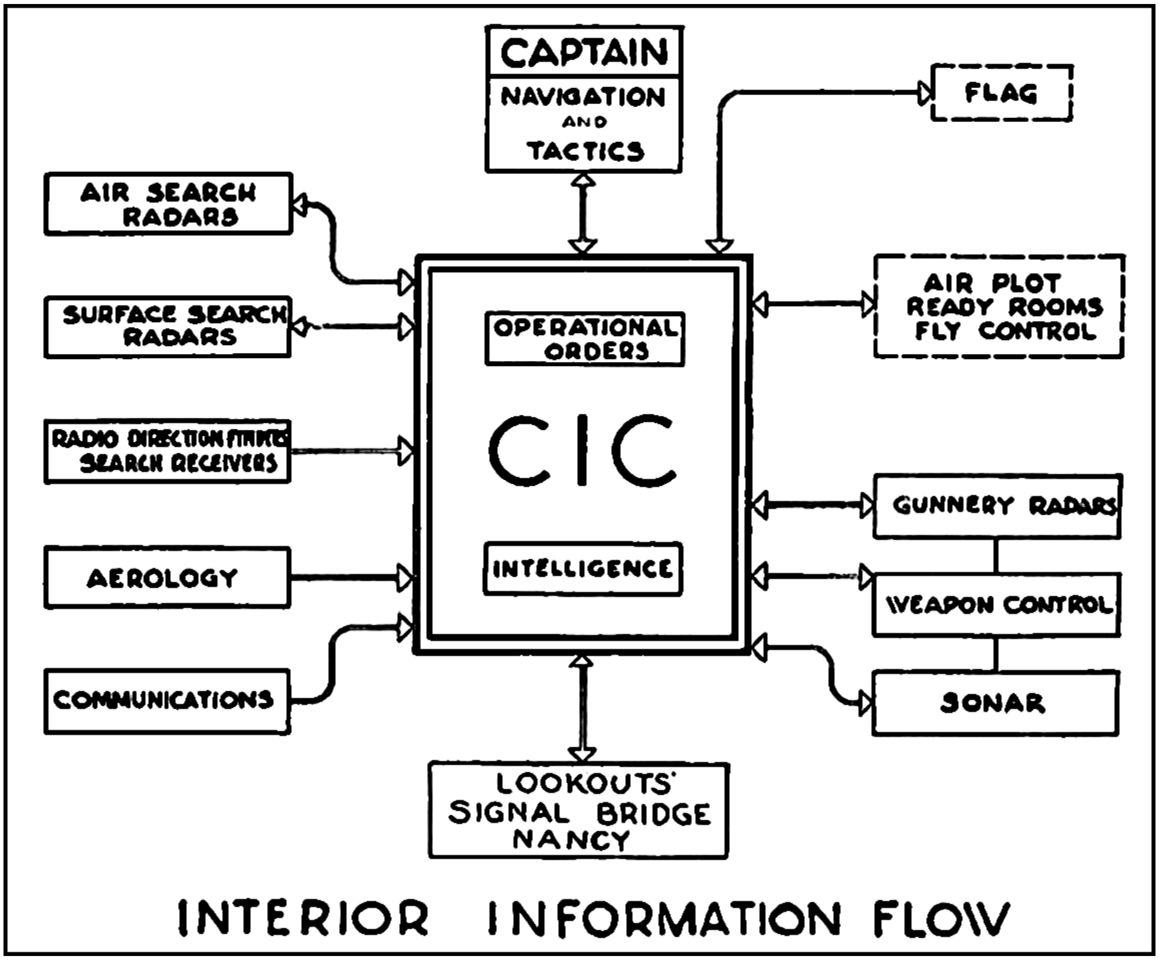

Figure 3. CIC Information Flow Within the Ship

Source: Ibid.

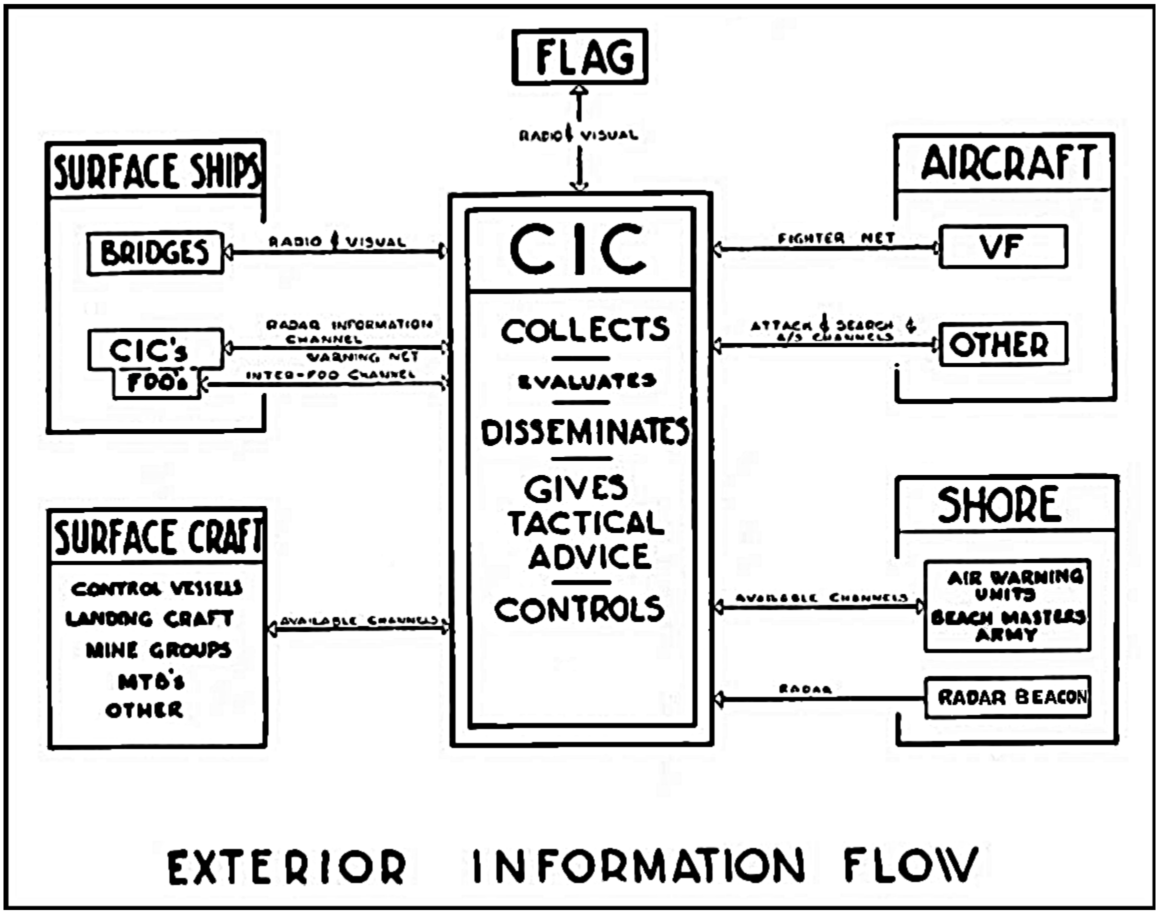

Figure 4. Flow of Information Between CIC and Other Units in the Force

Source: Ibid.

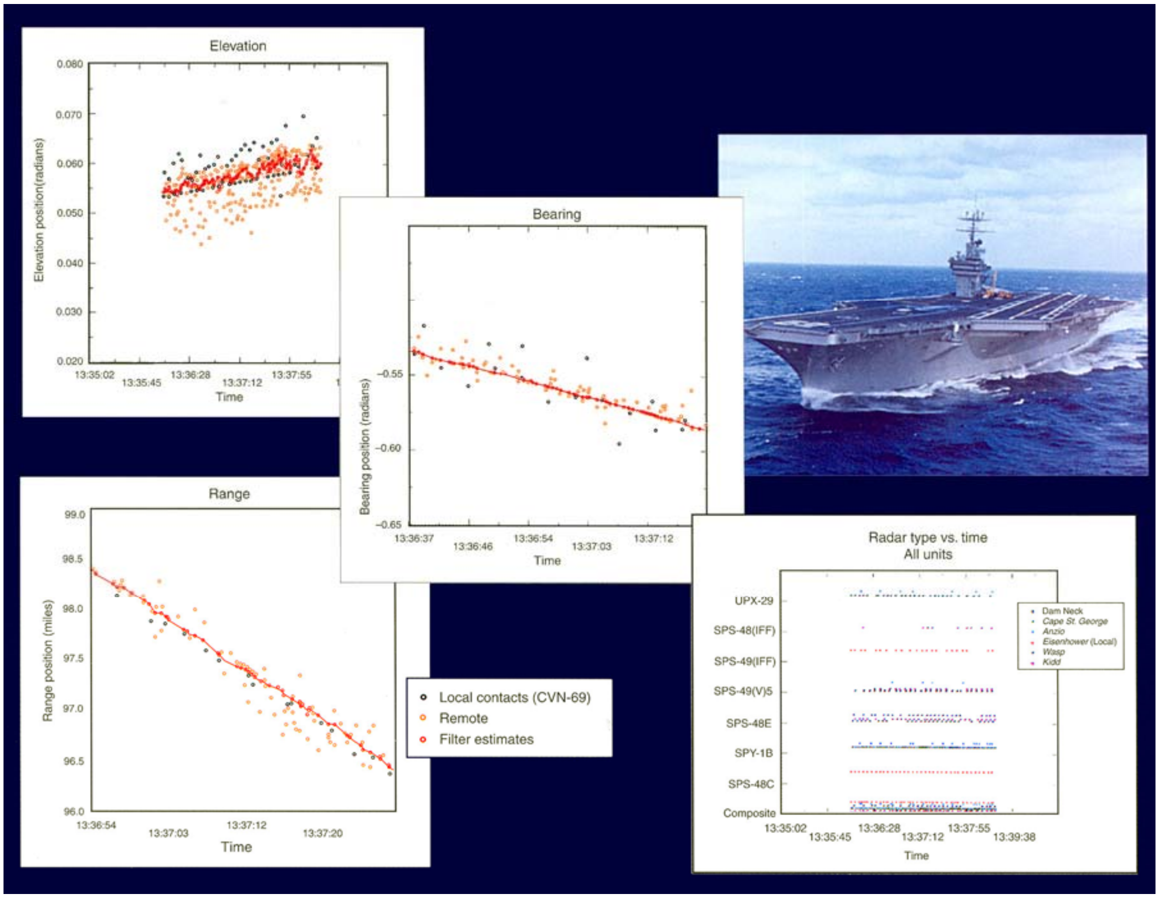

Figure 5. CEC composite tracking, showing how remote and local sensor data are combined. From tests conducted aboard USS *Dwight D. Eisenhower* (CVN 69), shown upper right.

Source: "The Cooperative Engagement Capability," *Johns Hopkins APL Technical Digest* 16, No. 4 (1995): 377-96, p. 388.

Instructor's Guide to CEC Case Study

Cooperative Engagement Capability is in many respects a "model" case, the kind that often springs first to mind in connection with the concept of *transformation*, in that it is essentially technological and military. It is in a sense broadly representative of such cases generally, and provides a vehicle for examining cross-cutting issues, in addition to those more specific to CEC. The following questions are suggested for discussion.

Question 1: Which drives transformation: technology or requirement? This was not a case in which a requirement was drawn up in advance of the fundamental decision about technology. CEC assumes the form it does because it was recognized in the 1980s that technology had created an opportunity. Moreover, the basic technology had been created without reference to the air defense problem. Thus, in this sense it was technology-driven. Yet we have seen that the technology was applied in response to needs that had already been perceived, in very primitive form, as much as 70 years earlier. Ever since the 1940s the Navy had striven relentlessly for means to close the gaps in tracking and engaging air threats. Would the advent of advance computational and communications technology have led to a development like CEC in the absence of such a background? Can we speak of a latent requirement, one widely recognized by experts in the field but not explicitly stated?

Question 2: To what extent can defense requirements drive technology in the 21st century? Radar and its associated technologies were created largely in response to military needs. The same is true of the origins of digital computing. Both of these major technology innovations took place before the middle of the 20th century, however. The later development of solid-state electronic devices was not initially prompted by military needs although NTDS played an important role in moving solid state electronics into computing. The technology which made the Aegis SPY-1 radar possible was largely developed under military auspices, although many component technologies were adapted from non-military fields.

For CEC itself, most of the basic technology came from civil sources. While the military was once a very important factor in computing and communications technologies, the non-military markets had become so vast by the 1980s that they were the major source of funding and demand for development. The military role in these areas is largely restricted to adaptation of technology developed for other purposes to military needs. Is this destined to be the pattern of the 21st century? If so, how can we assure that military needs can be met?

Question 3: What does technology truly transform? Admiral Alfred Thayer Mahan famously declared that the great technological transformations of his time did not affect the fundamental principles of war at sea. General William "Billy" Mitchell, by contrast, held that the introduction of aircraft had utterly transformed all of war, even to the level of basic principle.

Air defense is a whole branch of war that would never have come into being absent the airplane, and CEC is a product of needs for air defense (even though it also has secondary application to other needs). Does the existence of air defense affect the principles of war? What about radar? What about CEC?

If we are not to say that these innovations affect war at the level of fundamental principle, where do we place them? Can we locate them in the tripartite division of war between strategic, operational, and tactical levels? Should we systematically favor transformation at one level or another? Is a transformation at, say, the strategic level of war necessarily more significant than one at the tactical level? How can we meaningfully compare them?

Question 4: How much quantitative change amounts to a qualitative change? Admiral Arthur K. Cebrowski, the founding theorist of NCW, saw CEC as one of its cornerstones. He acknowledged that there were many elements of NCW in the World War II CIC and fighter direction net, but asserted that CEC marked such a departure from the past as to qualify as a change in kind, not just degree.[41]

It is of course obvious that the systems of World War II would be wholly inadequate in today's environment, so in that sense CEC is a revolutionary improvement. Yet within the context of the World War II environment, a system with CEC's functions (leaving aside questions of technological feasibility) would have represented a much more modest improvement in performance—the threat situation of that day simply did not give as much room for improvement, even had the radars that CEC would have had to work with then supported much added function.

In light of this should we conclude that CEC is a part of a sharp change which justifies claiming NCW as an entirely new phenomenon? Or should we see it as a phase in an evolutionary process ongoing since 1917? And how should our answer to this affect our assessment of its significance?

Question 5: How important are accidents of timing and circumstance? At the time that CEC began the Navy's major concern about air threats was mass coordinated ASCM attacks launched from Soviet bombers and/or submarines. The collapse of the Soviet Union brought change in this picture, but not as rapidly or completely as might be supposed. Successor states retained large elements of Soviet capability for some time. In addition they also attempted to market aircraft and missile systems to others. Thus concerns regarding Soviet-style massive coordinated missile attacks persisted well into the 1990s. CEC appeared perfectly suited to countering these threats, and very necessary.

But through the 1990s poverty forced the Soviet successor states to cut back their forces severely. At the same time, they found a limited market for their high-technology systems, selling only small numbers of missiles and aircraft to a few nations.

It became increasingly clear to the Navy's leadership that the primary need for the foreseeable future would be for joint and combined operations in littoral regions, facing regional or local threats. Massive coordinated threats were unlikely and massive air-launched threats especially so. But instead of defending ships far at sea, the Navy's air defenses would be called on to defend ships close to shore, to engage air threats to U.S. and allied forces ashore in the littoral, and to provide theater anti-ballistic missile defense. This would be true in the early phases of expeditionary operations especially, before substantial defense forces could be built up ashore.

CEC has been successfully adapted to these new demands and there is every reason to see it as remaining highly valuable. Nevertheless, it is reasonable to ask whether a different

[41] In conversations with the author.

course might have been pursued if the threat environment had been perceived differently at the time of CEC's definition. Do we need to do more to make our choices more robust in the face of uncertainties about the future? Or is CEC a good example of a transformation whose adaptability to changing needs validates the foresight of those who initiated it?